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DE 004005079 A

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(54) Determining magnetic field gradient tensors

(57) In order to determine all the linearly independent elements of the Nth order gradient tensor of a magnetic field a measuring device has at least 3N + 2 Nth order planar gradiometers (G1 - G9) disposed on at least three non-parallel and non-orthogonal surfaces. By these means, three-dimensional gradiometer structures become unnecessary.

FIG. 2

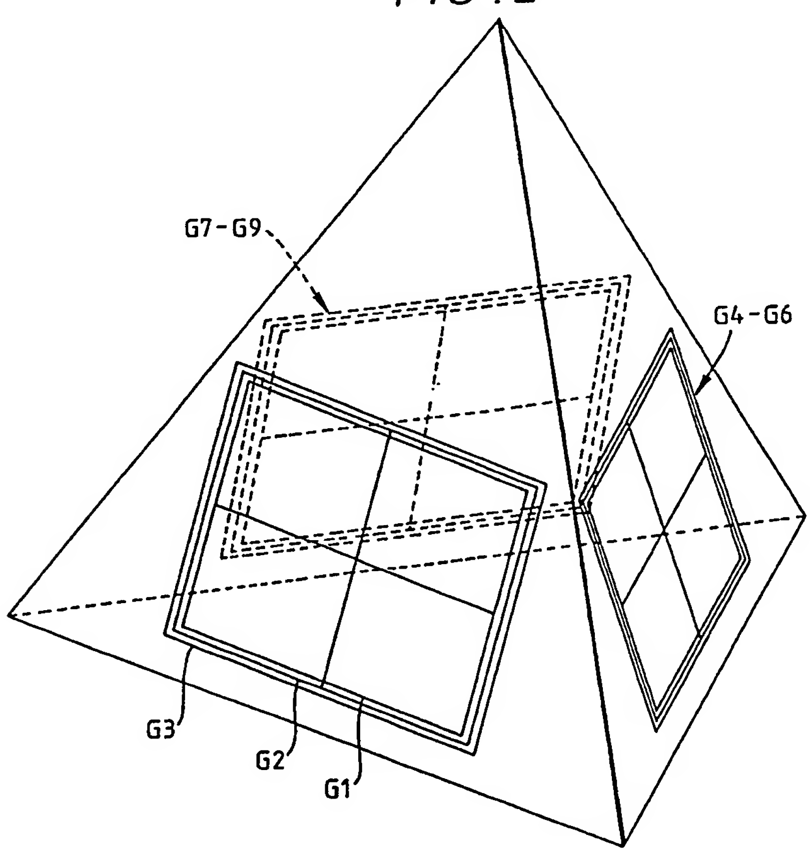

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FIG.1

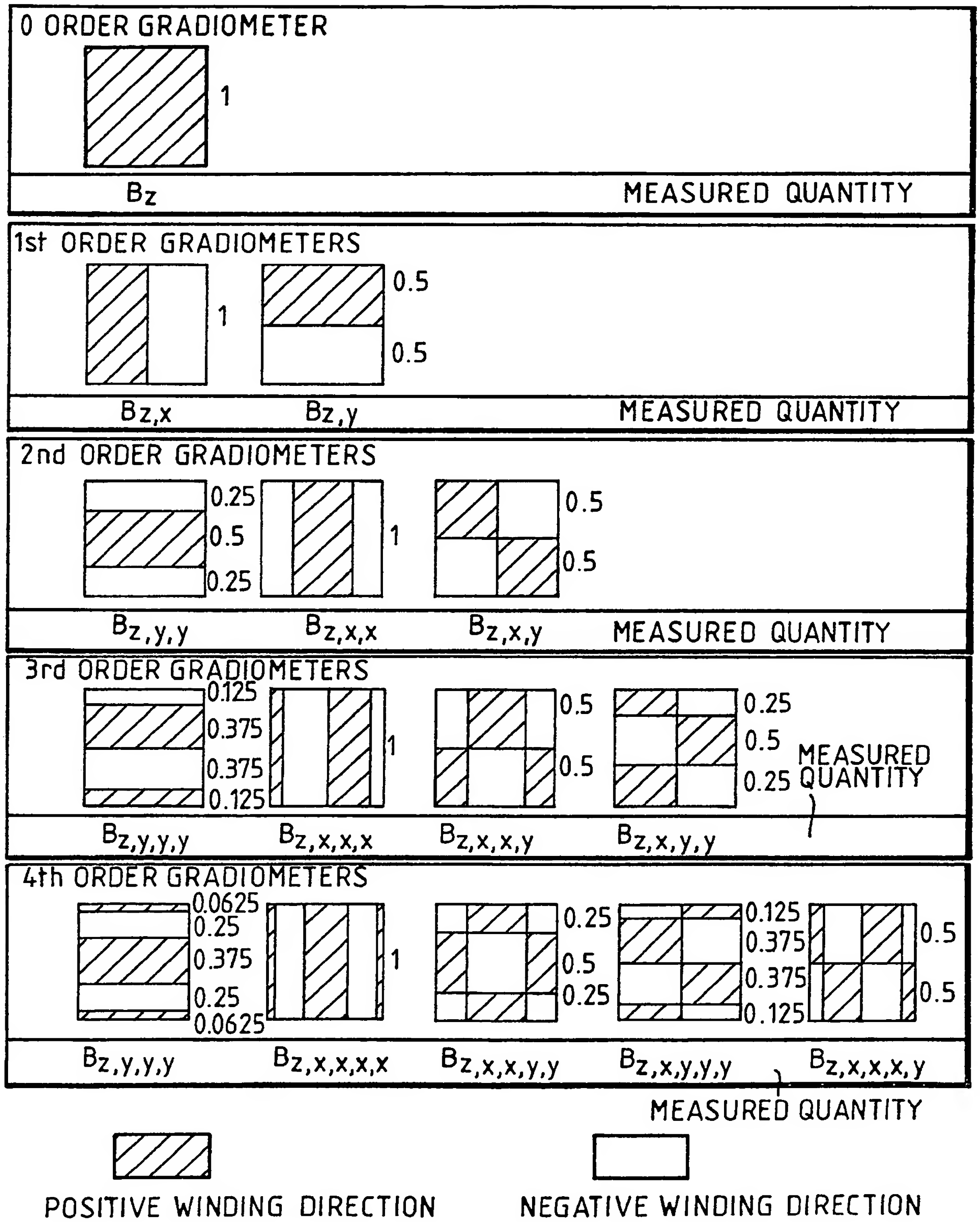
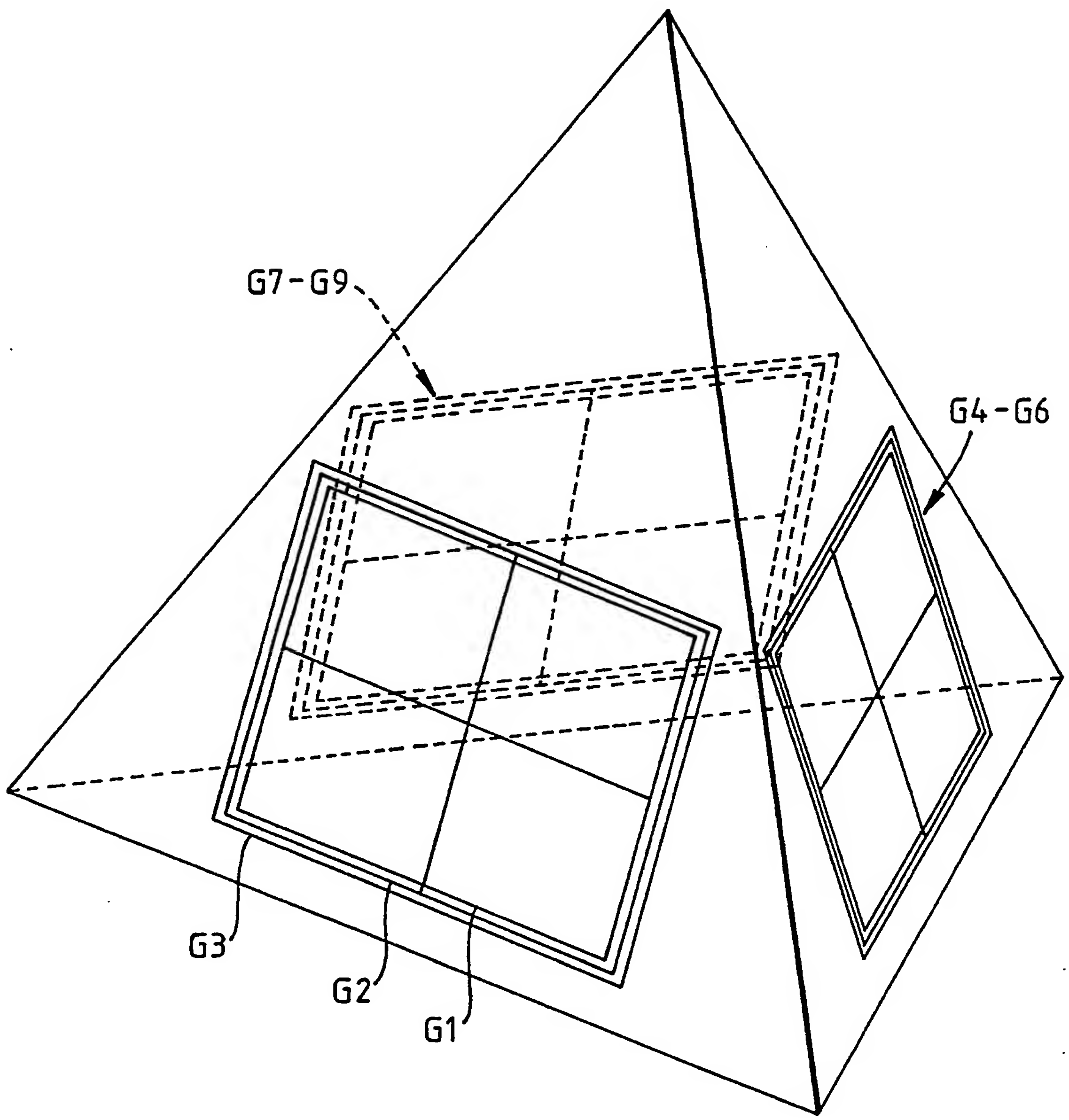

0 ORDER GRADIOMETER
1
Bz
MEASURED QUANTITY
1st ORDER GRADIOMETERS
1
0.5
0.5
Bz,x
Bz,y
MEASURED QUANTITY
2nd ORDER GRADIOMETERS
0.25
0.5
0.25
1
0.5
0.5
Bz,y,y
Bz,x,x
Bz,x,y
MEASURED QUANTITY
3rd ORDER GRADIOMETERS
0.125
0.375
0.375
0.125
1
0.5
0.5
0.25
0.5
0.25
MEASURED QUANTITY
Bz,y,y,y
Bz,x,x,x
Bz,x,x,y
Bz,x,y,y
4th ORDER GRADIOMETERS
0.0625
0.25
0.375
0.25
0.0625
1
0.25
0.5
0.25
0.125
0.375
0.375
0.125
0.5
0.5
Bz,y,y,y,y
Bz,x,x,x,x
Bz,x,x,y,y
Bz,x,y,y,y
Bz,x,x,x,y
MEASURED QUANTITY
POSITIVE WINDING DIRECTION
NEGATIVE WINDING DIRECTION

FIG. 2



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DEVICE FOR MEASURING LOCAL MAGNETIC FIELD DISTRIBUTIONS

This invention relates to a device for measuring all independent components of the Nth order gradient tensor (N>1) of a magnetic field.

Knowledge of the magnetic field components, and of the higher order spatial derivatives is necessary in order to characterise a local magnetic field distribution. This is clear, for example, from the Taylor series expansion of the magnetic field vector B (x):

$$B(x) = B|_o + \nabla B|_o \xi + \frac{1}{2}\nabla^2 B|_o \xi^2 + \ldots$$

$$= \sum_{N=0}^{\infty} \left[\frac{1}{N!}\nabla^N B|_o \xi^N\right],$$

where

$$\nabla^N B|_o$$

is the Nth order gradient tensor taken at the origin of a system of co-ordinates, which contains Nth order derivatives of the magnetic field components B_x, B_y, B_z according to the spatial co-ordinates x, y, z. An Nth order gradient tensor contains 3 + 2N independent linear components.

A measuring device by means of which the Nth order derivatives of the magnetic field can be measured is known as an Nth order gradiometer. According to this definition, a magnetometer for example, by means of which the magnetic field components B_x, B_y, B_z are measured, is a 0-order gradiometer.

An Nth order gradiometer comprises at least N + 1 field sensor coils, whereby more than N + 1 such coils are necessary for measuring given components.

The more accurately the local field distribution of a point is known, the more accurately the spatial field distribution at another point can be reconstructed or extrapolated. This is particularly significant for compensation of gradiometer devices of the type used in biomagnetic measuring technology or in the detection of magnetic anomalies. Acquisition of all the components of an Nth order gradient tensor, especially for N > 1, requires a large amount of space and considerable mechanical expenditure when conventional, wire-wound, three-dimensional coil devices are used. In addition, in principle wound coils exhibit relatively large errors. A gradiometer of this type is described by Wynn W.M. et al in "Advanced Superconducting Gradiometer / Magnetometer Arrays and a Novel Signal Processing Technique" (IEEE Transactions on Magnetics, Vol. Mag. - 11, No. 2, 1975, pages 701 - 707). Adjustment is carried out by means of superconducting auxiliary components.

Planar coils can easily be produced in thin film technology. However two-dimensional coil devices such as those used in SQUIDs are no longer sufficient to measure all linearly independent gradient components. In the case of a 1st order gradient tensor, these devices are only sufficient for measuring the non-diagonal components. Thus the gradients dB_z/dx and dB_z/dy can be determined by means of two coils on the x-y axis. The coils would have to be on two planes one above the other for the dB_z gradients, which is difficult to achieve with planar components. In thin film technology it is difficult to produce three-dimensional structures, e.g. to draw coatings over edges.

U.S. Patent No. 4,646,025 describes a device in which two coils superimposed in different planes are used to measure diagonal components, and two coils in the same plane are used to measure non-diagonal components.

The problems described also arise when determining gradient tensors with N > 1.

German Patent Application No. P 40 05 079.3-35 discloses means for measuring gradient tensor 1st order components (N=1). It is an object of the present invention to produce a device for determining all linearly independent components of an Nth order gradient tensor of a magnetic field when N > 1.

According to this invention, such a device comprises at least 3N + 2 planar Nth order gradiometers disposed on at least three non-parallel and non-orthogonal surfaces. Preferred features of the invention are set out in the dependent claims appended to this description.

A planar gradiometer is a gradiometer the field sensor coils of which are all disposed on a single plane.

On one surface a maximum of N + 1 co-planar, linearly independent gradiometers can be disposed. By linearly independent gradiometers we mean gradiometers which measure linearly independent components, hereinafter also known as orthogonal gradiometers. Gradiometers are co-planar with respect to one another when all the field sensor coils of all the gradiometers are disposed in a single plane.

Preferably N + 1 co-planar Nth order gradiometers are disposed on each of at least two of the surfaces, each gradiometer measuring linearly independent components.

Advantageously, on at least one surface, in addition to an Nth order gradiometer or gradiometers, there may be further co-planar gradiometers of less than the Nth order. In a particularly advantageous embodiment, the following gradiometers are disposed together on the same surface:

N + 1	Nth order gradiometers
N	(N-1) - order gradiometers
N - 1	(N-2) - order gradiometers
.	
.	
1	0-order gradiometer,

i.e. altogether ((N+1)*(N+2))/2 gradiometers, where gradiometers of the same order measure orthogonal components.

In order that interaction between the gradiometers and field sensor coils is minimal, advantageously each of the coils may comprise only a single turn.

A further reduction of interaction is achieved if the field sensor coils of a single gradiometer are disposed in the form of a matrix. In this connection the field sensor coils of an Nth order gradiometer should be disposed in m + 1 lines and n + 1 columns, with the additional condition that m + n = N. The lines and columns each correspond to a differentiation direction, i.e. in the x, y or z axis, for example. The coil area of the field sensor coil in line i and column j is determined by the following relationship:

$$A_{ij} = A_o * \left[\frac{1}{2^m}\binom{m}{i}(-1)^i\right] * \left[\frac{1}{2^n}\binom{n}{j}(-1)^j\right],$$

where i = 0,...,m and j = 0,...n.

This gives the positive or negative winding direction and A_o indicates the total surface area of the gradiometer, which can for example be in the form of a square. The symbol "*" is the multiplication operator.

If this relationship is maintained for each gradiometer, mutual interaction is minimal, precisely when all

gradiometers disposed on the same surface are centred and laminated substantially flush one above another.

This has the advantage that since all gradiometers disposed on the same surface can be integrated in a chip, optimum numerical adjustment is possible in order to suppress interference. In addition, wound coils with their naturally high error levels are avoided. Complicated lamination processes in which superconducting connections must be drawn over edges, are not necessary.

The described device has the following particular applications:

- detection of residual munitions mines etc., with the possibility of shape recognition;
- diagnostic equipment for measuring magnetocardiograms and magnetoencephalograms, with or without use of screening chambers;
- determination of the point and direction of a magnetic probe unit inside the body, eg in surgery / endoscopy;
- geological prospecting with airborne and stationary systems;
- non-destructive materials testing (low frequency eddy current processes in order to test for cracks in the interior of thick-walled structures, from the outside).

The invention will now be described by way of example with reference to the drawings, in which:

Figure 1 is a series of diagrams showing planar zero-order to 4th order gradiometers in accordance with the invention;

Figure 2 is an oblique view of a planar gradiometer in accordance with the invention.

Referring to Figure 1, a series of 0 to 4th order planar gradiometers used in accordance with the invention has in each row N + 1 orthogonal Nth order gradiometers. In the figure it is specified which components of the gradient tensor can be measured by means of the individual gradiometers. It is assumed that the gradiometers shown are disposed on the x/y plane of a system of co-ordinates. The expression $B_{z,x,y,}$ for example, designates the derivative of the z components of the magnetic field according to the spatial co-ordinates x and y.

The shaded and unshaded areas represent the coil surfaces of the individual field sensor coils of a gradiometer. Correspondingly the coil turns are represented as borders of the shaded and unshaded surfaces. A shaded surface designates a positive winding direction, while an unshaded surface designates a negative winding direction. The individual field sensor coils need not necessarily be square or rectangular. Gaps between the coils are also possible.

The above description applies to the surface areas of the field sensor coils of all the gradiometers shown in Figure 1. The values for m and n from the above formula, e.g. for the illustrated 4th order gradiometers, are the following from left to right: (m,n) = (4,0), (0,4), (2,2), (3,1), (1,3).

The figures on the right-hand side of each gradiometer in Figure 1 represent respective surface areas, normalised to 1.

Referring to Figure 2, a device in accordance with the invention has nine planar gradiometers G1 - G9 arranged on three surfaces of a tetrahedron for measuring the components of the 2nd order gradient tensor. On each of the three tetrahedron surfaces there are three orthogonal planar gradiometers G1 - G3, G4 - G6, G7 - G9 disposed in layers

one over another. The bottom gradiometers are represented symbolically by projecting edges. The superimposed gradiometers can be produced by thin film technology methods. A thin insulation layer is applied between each gradiometer.

CLAIMS

1. A device for determining all linearly independent components of the Nth order gradient tensor of a magnetic field, where N > 1, comprising at least 3N + 2 planar Nth order gradiometers disposed on at least three non-parallel and non-orthogonal surfaces.

2. A device according to claim 1, wherein the gradiometers are disposed on the surface of a polyhedron with at least three non-parallel and non-orthogonal surfaces, such as a pyramid with four, five, six, seven or more outer surfaces, an octohedron, a dodecahedron, or an icosahedron.

3. A device according to claim 1 or claim 2, having on each surface N + 1 Nth order gradiometers for measuring linearly independent components.

4. A device according to any preceding claim, having additional gradiometers of order lower than the Nth order, disposed on at least one surface.

5. A device according to claim 4, having the following gradiometers disposed on at least one surface:

N + 1	Nth order gradiometers
N	(N - 1) - order gradiometers
N - 1	(N - 2) - order gradiometers
.	
.	
1	0-order gradiometer.

6. A device according to any preceding claim, characterised in that the gradiometers disposed on the same surface are centred and laminated flush one above another.

7. A device according to any preceding claim, including gradiometers in which each field sensor coil thereof comprises a single coil.

8. A device according to any preceding claim, having an Nth order gradiometer the field sensor coils of which are disposed in matrix form in m + 1 lines and n + 1 columns, and the following relationship applies for the coil area A_{ij} of the field sensor coil in line i and column j:

$$A_{ij} = A_o * \left[\frac{1}{2^m}\binom{m}{i}(-1)^i\right] * \left[\frac{1}{2^n}\binom{n}{j}(-1)^j\right],$$

where i = 0,1,...m and j = 0,1,...,n.

9. A device for determining all the linearly independent components of the first order gradient tensor of a magnetic field, having at least 5 planar first order gradiometers disposed on at least 3 non-parallel and non-orthogonal surfaces, including a gradiometer the field sensor coils of which are disposed in matrix form in m + 1 lines and n + 1 columns, the coil area A_{ij} of the field sensor coil in line i and column j being determined by:-

$$A_{ij} = A_o * \left[\frac{1}{2^m}\binom{m}{i}(-1)^i\right] * \left[\frac{1}{2^n}\binom{n}{j}(-1)^j\right],$$

where i = 0,1,...m and j = 0,1,...,n.

10. A device according to claim 9, wherein gradiometers disposed on the same surface are centred and laminated substantially flush over each other.

11. A device according to claim 9 or claim 10, wherein each gradiometer field sensor coil comprises a single turn.

12. A device for determining all linearly independent components of the Nth order gradient tensor of a magnetic

field, the device being constructed and arranged substantially as herein described with reference to the drawings.

Patents Act 1977
Examiner's report to the Comptroller under Section 17 (The Search Report)

Application number

GB[illegible]16217.1

Relevant Technical fields

(i) UK Cl (Edition K) G1U UR33 022

(ii) Int Cl (Edition 5) G01R 33/022

Search Examiner

K F J NEAL

Databases (see over)

(i) UK Patent Office

(ii) ONLINE DATABASES: WPI

Date of Search

2 OCTOBER 1992

Documents considered relevant following a search in respect of claims 1 TO 8

Category (see over)	Identity of document and relevant passages	Relevant to claim(s)
A	DE 4005079 A (DORNIER)	

SF2(p) SJJ - doc99\fil000829

Category	Identity of document and relevant passages	Relevant to claim(s)

Categories of documents

X: Document indicating lack of novelty or of inventive step.

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